Improving Radiation Shielding and Mechanical Properties of Concrete Incorporating Barite, Magnetite, and Serpentine Aggregates

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Abstract

This paper discusses the mechanical properties and radiation shielding of concrete with heavy aggregates like barite, magnetite, and serpentine. We prepared various concrete mixes using different amounts of these aggregates. We measured their compressive strength, workability through slump tests, density, and radiation attenuation. Our results showed that concrete with barite and magnetite provides the best gamma-ray and thermal neutron shielding, mainly because of their higher density. The mixture with magnetite also had the highest compressive strength among the samples. The barite concrete sample demonstrated the best performance for applications needing strong radiation protection, thanks to its excellent shielding capabilities and density. This study emphasizes the importance of selecting the right aggregates to enhance both the mechanical and protective properties of concrete in various practical applications.

Keywords: linear attenuation coefficient (μ), tenth-value layer (TVL), half-value layer (HVL), Radiation shielding, Mechanical properties

1. Introduction

Concrete is widely used for radiation shielding in reactors and buildings. It's low-cost and has good mechanical quality. This material includes nuclei with relatively high atomic numbers and a mix of hydrogen and light nuclei (Ikraiam et al. 2009). Its aggregate component, made of heavy materials, boosts concrete's shielding qualities. Thus, it effectively reduces the strength of photons and neutrons (El-Sayed 2002; Akkurt et al. 2012).

Heavyweight concrete uses natural minerals like hematite, magnetite, and barite as aggregates. These heavy aggregates have high specific gravity and absorb radiation, enhancing concrete's protective properties. Currently, heavyweight concrete shields nuclear power plants, radiotherapy rooms, and aids in transporting and storing radioactive waste. It needs both high strength and high density. High-strength, heavyweight concrete serves protective purposes when it meets strength and radiation shielding requirements.

A nuclear power plant's core is housed in a reactor concrete building, which typically features a dual containment system. This system includes a primary (inner) containment structure and a secondary (outer) containment structure. The structure containing the reactor is crucial. It must endure strong and penetrating radiation.

This research aims to explore using concrete components to create high-performance radiation shielding

concrete. Different aggregate types may enhance protection against gamma and neutron radiation. The goal is to find mixtures that offer suitable mechanical strength and protective properties.

For this purpose suitable aggregates were selected. Three types of coarse aggregates were used:

- Magnetite
- Barite
- Serpentine

In this study different concrete mixtures with different aggregate were prepared and their physical and mechanical properties were evaluated. The porpuse of these tests were to examine the effect of aggregate type on the compressive strength and radiation attenuation of the concrete. Compressive strength test was conducted to determine the mechanical strength of the concrete. Additionally gamma and neutron radiation attenuation test was performed using radioactive source and radiation measuring devices to assess the protective performance of different concrete mixtures.

The results of this research can aid in selecting the best material compositions for producing high-performance protective concrete, significantly improving the safety and efficiency of structures in nuclear and radiotherapy applications.

2. Methodology of research

2.1. Materials

The coarse and fine aggregates in this study came from local mines in Iran. We used an XRF spectrometer to check their chemical composition. This ensured the materials were suitable for protective concrete. The analysis was done with the XRF Spectrometer PW1400, as shown in Table 1.

Table 1. Chemical composition of the concrete samples

Oxides (w/w%)	B1-4	M3	B3-5	B1-1	C1-5	B2-4	M2-2
Al2O3	1.24	4.68	1.57	0.95	1.32	2.13	0.88
SiO2	12.79	35.83	14.53	16.68	31.42	19.12	15.47
P2O5	0.66	0.44	0.87	0.64	0.64	0.59	0.58
SO3	14.58	3.73	19.68	4.56	3.61	14.55	4.22
CI	300 (ppm)		250 (ppm)		250 (ppm)	300 (ppm)	-
K2O	0.49	1.53	0.53	0.34	0.36	0.9	0.39
CaO	29.03	15	20.36	41.29	48.12	24.36	48.35
TiO2	0.15	0.85	-	0.18	0.14	0.3	0.16
V2O5	750 (ppm)	-	-	-	-	-	-
Cr2O3	250 (ppm)	0.11	400 (ppm)	400 (ppm)	0.35	500 (ppm)	350 (ppm)
MnO	0.17	0.11	0.2	0.13	0.19	0.17	0.1
Fe2O3	13.27	35.34	15.7	34.09	9.18	16.63	27.94
CuO	750 (ppm)	300 (ppm)	750 (ppm)	350 (ppm)	-	800 (ppm)	250 (ppm)
ZnO	750 (ppm)	400 (ppm)	450 (ppm)	450 (ppm)	300 (ppm)	350 (ppm)	350 (ppm)
SrO	0.5	850 (ppm)	0.49	0.13	0.2	0.39	0.15
PbO	0.21	-	0.21	-	-	0.16	-
SnO2	350 (ppm)	-	275 (ppm)	-	400 (ppm)	350 (ppm)	-
BaO	25.3	0.49	23.65	0.3	0.32	19.63	0.26
ZrO2	-	250 (ppm)	-	-	-	-	-
MgO	-	1.29	-	-	2.61	-	-
Cs2O	-	-	850 (ppm)	-	-	550 (ppm)	-
NiO	-	-	-	-	0.31	-	-

2.2. Mix Proportions

Creating a concrete mix design means choosing the right ingredients. These include cement, water, superplasticizer (SP), silica fume (SF), and aggregates like serpentine, barite, and magnetite. You must also determine the correct proportions for each ingredient. This process aims to produce a cost-effective concrete mixture. It should maintain the required strength, durability, and workability. Additionally, it needs to be suitable for radiation shielding, aligning with the study's goals. The mix proportions of the concrete mixes are provided in Table 2.

Table 2. Concrete Mix Proportions

Sample Number	Cement (kg)	Water (lit)	Fine Aggregate (kg)	Barite Aggregate (kg)	Barite (5-10 mm) (kg)	Serpentine Aggregate (kg	Serpentine (5-10 mm) (kg)	Serpentine (10-20 mm) (kg)	Magnetite Aggregate (kg)	Magnetite (5-10 mm) (kg)	Normal Gravel (5-10 mm) (kg)	Normal Gravel (10-20 mm) (kg)	Micro Silica (kg)	Naphthalene (g)	W/C
B2-4	7.92	2.75	7.85	12.00	3.00	-	-	-	-	-	3.63	11.00	0.80	150.00	0.35
C1-5	8.00	4.00	15.40	-	-	2.20	6.84	10.46	-	-	-	-	0.80	240.00	0.40
M2-2	8.70	3.20	7.86	-	-	-	-	-	11.00	3.30	3.63	11.00	0.90	240.00	0.36
B3-5	7.92	2.87	3.50	16.20	2.00	-	-	-	-	-	5.85	8.00	0.80	150.00	0.36
M3	7.92	3.50	3.85	-	-	-	-	-	13.30	2.87	3.73	10.15	0.80	240.00	0.44
B1-1	7.92	2.90	5.35	14.40	2.50	-	-	-	-	-	3.73	10.15	0.80	185.00	0.36

2.3. Mixing, curing and testing speciments

Concrete mixing was prepared based on C 192/C 192M standard. The mixing method of the materials was done in a mixer with a capacity of 20 liters in the following order: at first for each mixture, coarse aggregates and fine aggregates and then cement are mixed dry for 2 minutes. Approximately 80% water and additives were added and then the mixer was started. After 3 minutes of mixing, the remaining of the water was gradually added to the running mixer. Then it was stopped for 3 minutes and mixed again for 2 minutes. After the mixing process was completed, a slump test was performed on the fresh concrete to determine the workability according to EN 12350-2. All concrete samples were poured in three layers in a 150x150x150 mm steel molds. Then, the concrete samples were covered with a plastic layer to prevent water evaporation and then kept at room temperature for 24 hours. After removing the molds, the concrete samples were immersed in the water tank for 28 days. Proper curing of concrete is very important to achieve the desired compressive strength and also to make durable concrete.

2.3.1. Compressive strength

This test was determined at the curing ages of 28 and according to BS en 12390-3-2019 . The test was carried out using a 300 ton azmmon company compression testing machine and a loading rate of 0.6 MPa/s. The compressive strength results of concrete samples are given in figure 1.

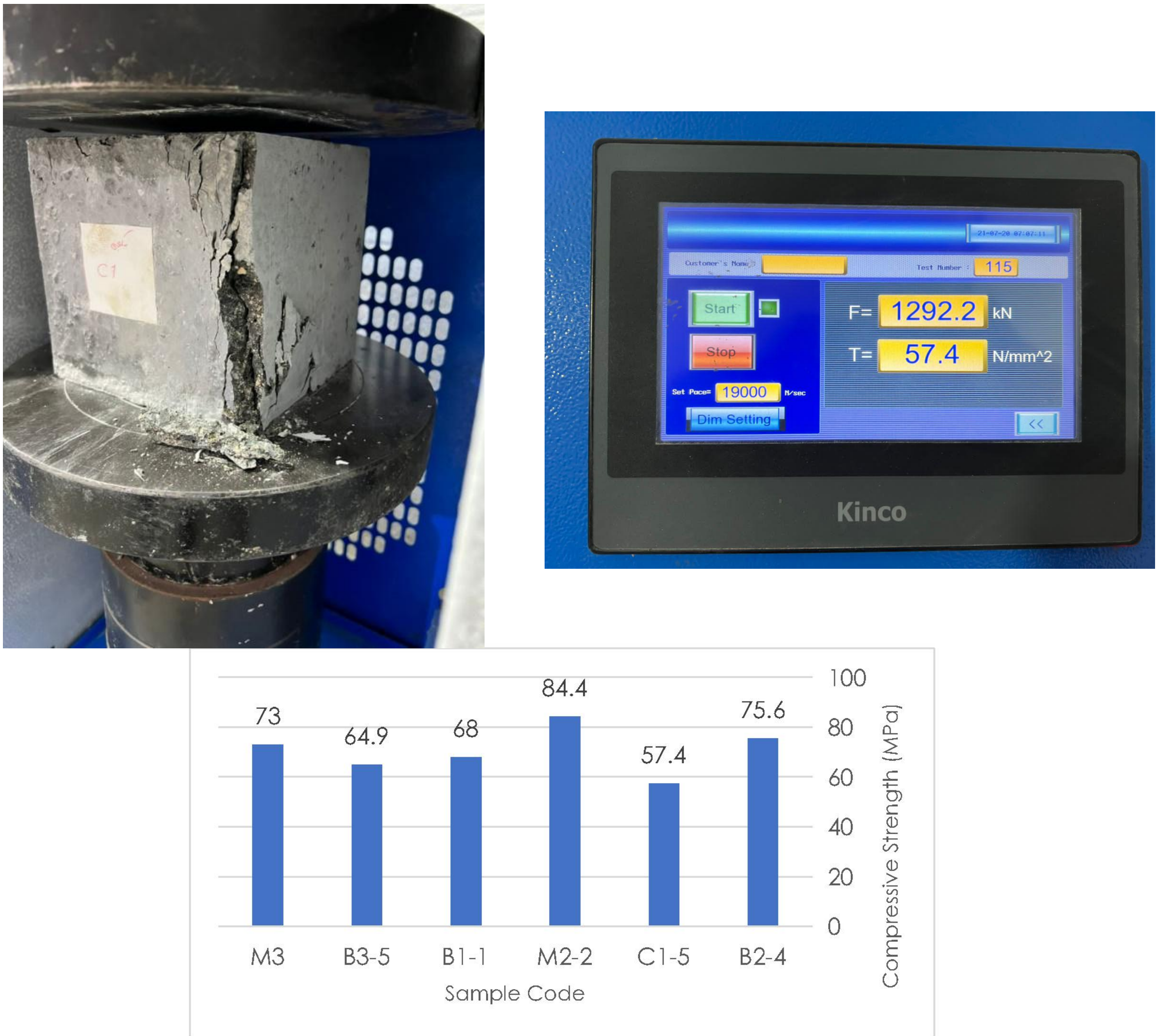

Figure 1. Compressive Strength (MPa)

2.3.2. Slump flow test

This test is a simple and effective way to check workability. It followed EN 12350-2 standards. Figure 2 and Table 3 show the slump flow measurements for different mix batches. These batches used various aggregates: natural sand, magnetite, barite, and serpentine. The slump value reflects the concrete's workability. A higher slump value means the concrete is more fluid, while a lower value indicates it is stiffer. The study found that all mixes had slump values between 16-24 cm. Barite had the highest slump, and the mix of barite and magnetite showed the highest slump flow.

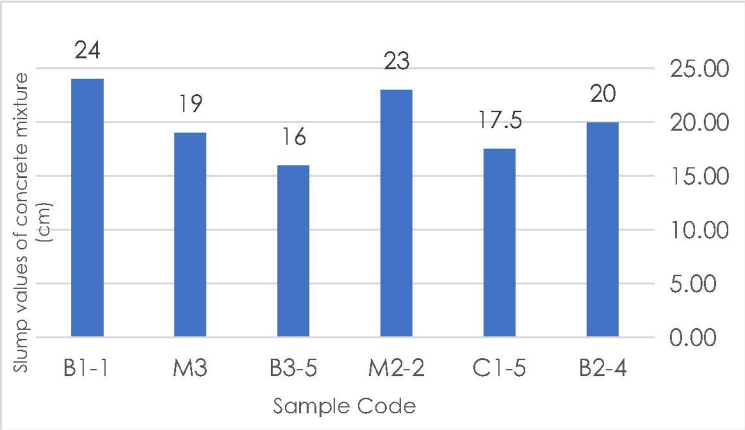

Figure 2. Slump values of concrete mixture (cm)

Table 3. Slump values of concrete mixture (cm)

Sample Number	Slump values, cm
B2-4	20
C1-5	17.5
M2-2	23
B3-5	16
M3	19
B1-1	24

2.3.3. Density of concrete

The density of fresh and hardened concrete was performed according to EN 12350-6. The values of density of concrete samples is shown in figure 3.

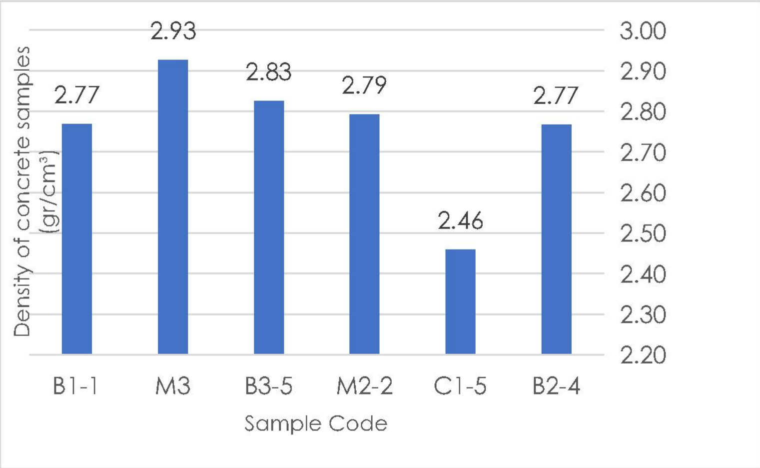

Figure 3. Density of concrete samples (gr/cm³)

2.3.4. Radiation attenuation test

The linear attenuation coefficient (μ), half-value layer (HVL), and tenth-value layer (TVL) samples prepared with various types of heavyweight aggregates were evaluated at 28 days. Table 4 shows the μ of the studied samples measured using different sample. Total neutron and photon fluxes at the End of the collimator in the "E" Tehran Research Reactor beam tube is 2 x 10^6 n/cm^2.s in power 5 MW (Figure 4) . This study investigates the effectiveness of various concrete samples in attenuating gamma and thermal neutron radiation. By analyzing the linear attenuation coefficients (μ) for each sample, we assess the shielding capabilities of different types of concrete, including barite, serpentine, and magnetite concrete.

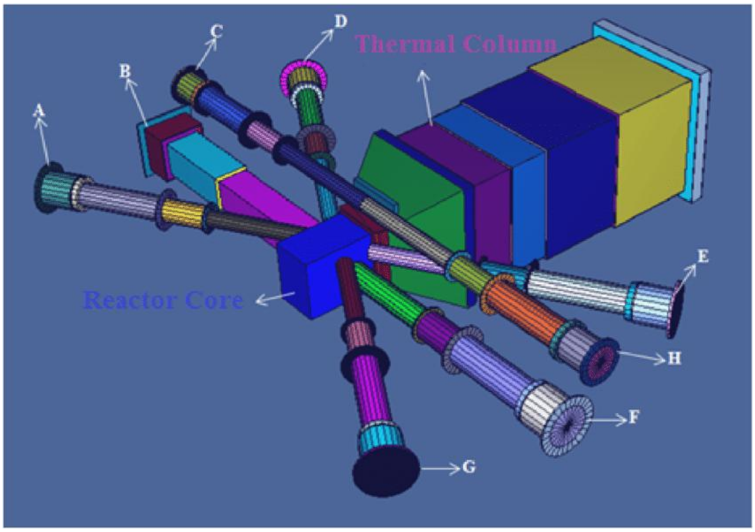

Figure 4. 3D drawing of a TRR reactor beam tubes

The linear attenuation coefficient (m) has been obtained from the solution :

$$\mu = \frac{I}{x} ln\left(\frac{I_o}{I}\right) \; HVL = \frac{ln\,2}{\mu} \; \mathrm{TVL} = \frac{\ln 10}{\mu}$$

The linear attenuation coefficients for gamma (μ_gamma) and thermal neutron (μ_thermal) radiation were calculated for six different concrete samples. The results are as follows:

Table 4. Linear Attenuation Coefficients

Sample Number	Gamma Attenuation Coefficient	Thermal Neutron Attenuation Coefficient
B2-4 (Barite Concrete)	0.1862 cm^{-1}	0.2276 cm^{-1}
C1-5 (Serpentine Concrete)	0.1799 cm^{-1}	0.2155 cm^{-1}
M2-2 (Magnetite Concrete)	0.1826 cm^{-1}	0.2314 cm^{-1}
B3-5 (Barite Concrete)	0.1849 cm^{-1}	0.2509 cm^{-1}
M3 (Magnetite Concrete)	0.1815 cm^{-1}	0.238 cm^{-1}
B1-1 (Barite Concrete)	0.1809 cm^{-1}	0.2424 cm^{-1}

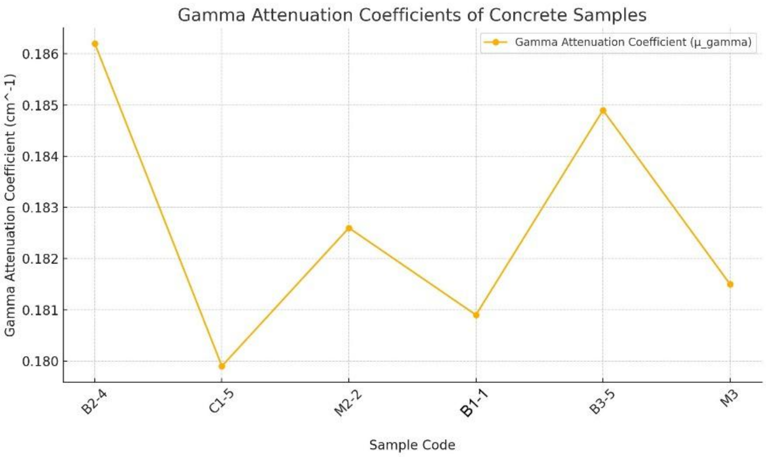

Figure 5. Gamma Attenuation Coefficients of Concrete Samples

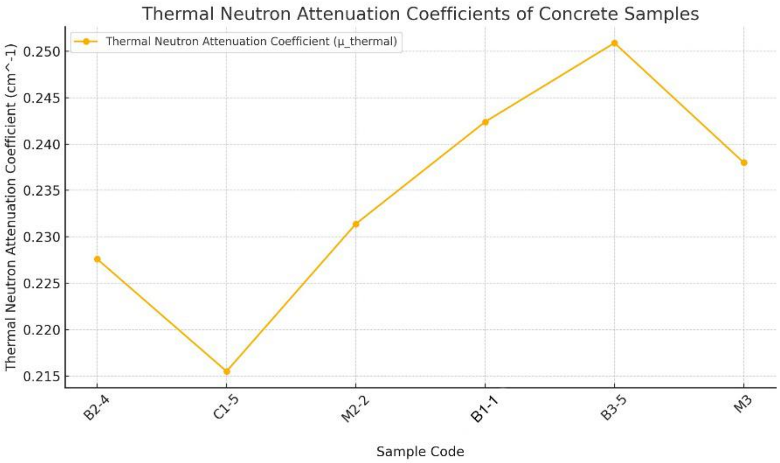

Figure 6. Thermal Neutron Attenuation Coefficients of Concrete Samples

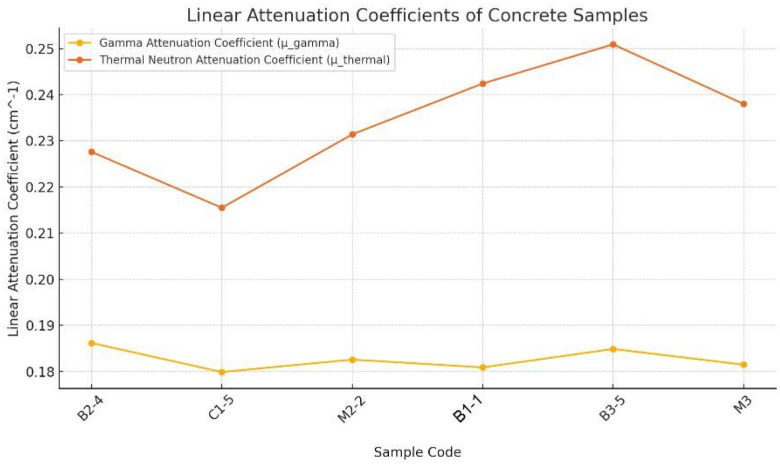

Figure 7. Linear Attenuation Coefficient for Gamma and Thermal Neutron

Based on the type of concrete, the following observations and figures 5,6 and 7 can be made regarding their effectiveness in shielding against gamma and thermal neutron radiation.

Barite Concrete:

B2-4 and B3-5 samples are made of barite concrete, known for its high density and excellent radiation shielding properties. B2-4 has the highest gamma attenuation coefficient, making it particularly effective for gamma radiation shielding. B3-5 has the highest thermal neutron attenuation coefficient and is also highly effective for gamma radiation. This sample is the best overall for comprehensive radiation shielding.

Serpentine Concrete:

C1-5 is made of serpentine concrete, which is commonly used for its neutron shielding properties. Despite its specific use for neutron shielding, the μ_gamma and $\mu\_thermal$ values are lower than those of barite and magnetite concrete, indicating that while it offers some protection, it is less effective compared to other types.

Magnetite Concrete:

M2-2 and M3 are made of magnetite concrete, which is known for its density and effective radiation shielding. M2-2 shows good performance in both gamma and thermal neutron attenuation, making it a strong candidate for shielding applications where both types of radiation are present. M3 also demonstrates good attenuation properties, particularly for thermal neutron radiation.

This analysis examines the linear attenuation coefficient (μ) and the calculations of the Half-Value Layer (HVL) and Tenth-Value Layer (TVL) for gamma radiation and thermal neutrons in different concrete samples. The aim is to assess the efficiency of various concrete samples in radiation attenuation and to identify the best sample for shielding applications.

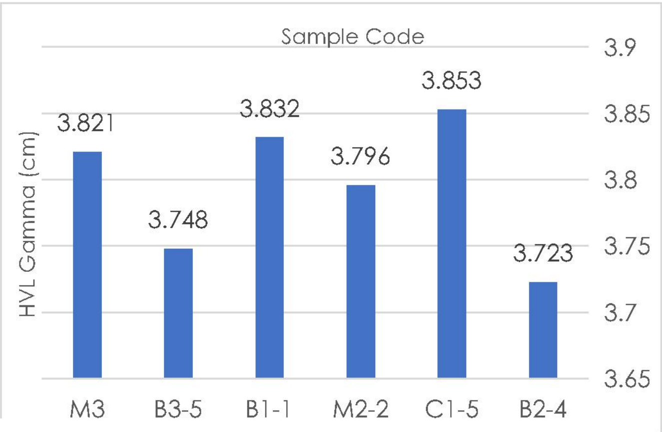

Figure 8. HVL Gamma (cm)

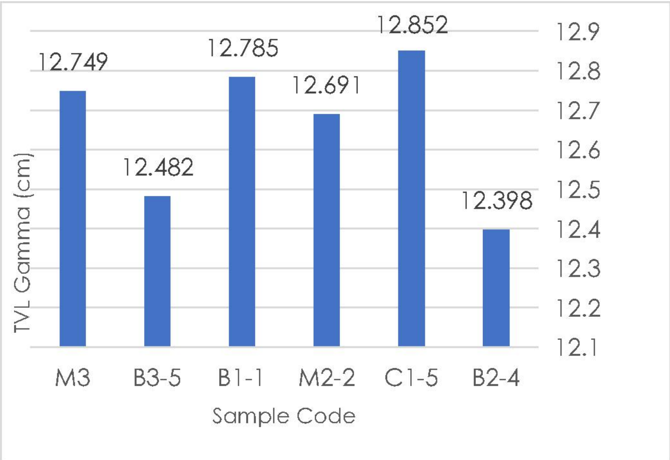

Figure 9.TVL Gamma (cm)

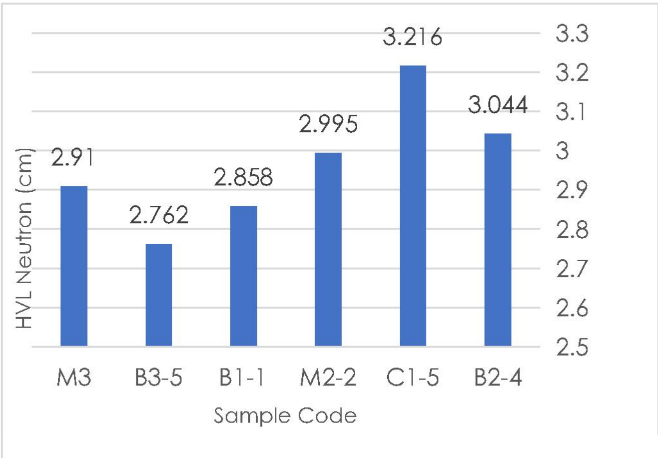

Figure 10. HVL Neutron (cm)

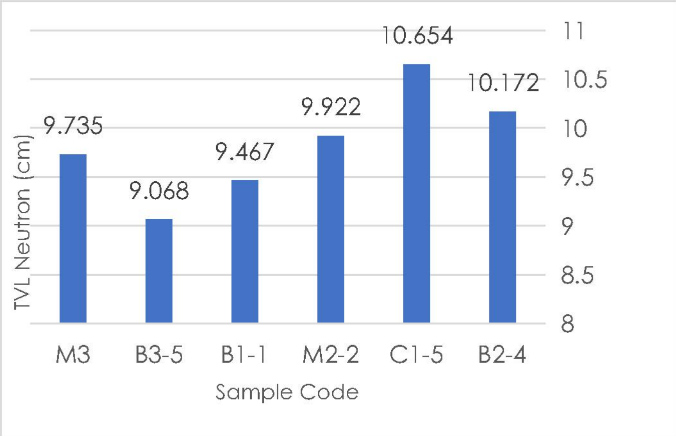

Figure 11. TVL Neutron (cm)

Figures 8, 9, 10 and 11 show the HVL and TVL values of concrete mixes. These results show that the B2-4 and B3-5 samples require the least thickness to reduce the gamma radiation intensity by half, indicating higher efficiency in gamma radiation shielding. Additionally, for reducing the intensity to one-tenth of the original value, the B2-4 and B3-5 samples again demonstrate superior performance. The results show that the B3-5 and B1-1 samples require the least thickness to reduce the thermal neutron intensity by half, indicating higher efficiency in thermal neutron shielding. Additionally, for reducing the intensity to one-tenth of the original value, the B3-5 and B1-1 samples again demonstrate superior performance.

3. Results and discussion

3.1. Density:

The incorporation of magnetite and barite notably increased the density of the concrete, which is directly related to their high specific gravity. Higher density is advantageous not only for mechanical strength but also for improving radiation shielding effectiveness. Serpentine, while increasing the concrete's density compared to normal aggregates, did so to a lesser extent than magnetite and barite. The variation in density among the

samples also impacted their overall performance, particularly in terms of radiation protection.

3.2. Compressive strength:

The compressive strength of different concrete types varies significantly.
Highest: Magnetite M2-2 with 84.4 MPa
Lowest: Serpentine C1-5 with 57.4 MPa
In general, Barite concretes have lower compressive strength compared to Magnetite concretes. This is observed in samples B2-4, B3-5, and B1-1.
The results revealed that the inclusion of magnetite and barite significantly enhances the compressive strength of concrete. Magnetite's high specific gravity contributed to a denser and more robust concrete matrix, resulting in superior compressive strength. Barite also improved the strength of the concrete, though to a slightly lesser extent than magnetite. Serpentine, while contributing positively, did not achieve the same level of strength enhancement as the other two aggregates. This indicates that magnetite and barite are more effective for applications requiring high-strength concrete.

3.3. Radiation attenuation test:

a) Best Overall Sample:
B3-5 (Barite Concrete): Highly effective for both gamma and thermal neutron shielding.
- Gamma Attenuation Coefficient: 0.1849 cm^{-1}
- Thermal Neutron Attenuation Coefficient: 0.2509 cm^{-1}

Ideal for applications requiring robust protection from both gamma and thermal neutron radiation.

b) Good Alternatives:
M2-2 (Magnetite Concrete):
- Gamma Attenuation Coefficient: 0.1826 cm^{-1}
- Thermal Neutron Attenuation Coefficient: 0.2314 cm^{-1}

Effective for both gamma and thermal neutrons, making it a viable alternative to B3-5.
M3 (Magnetite Concrete):
- Gamma Attenuation Coefficient: 0.1815 cm^{-1}
- Thermal Neutron Attenuation Coefficient: 0.2380 cm^{-1}

Particularly effective for thermal neutron shielding and suitable for comprehensive radiation protection.
B1-1 (Barite Concrete):
- Gamma Attenuation Coefficient: 0.1809 cm^{-1}
- Thermal Neutron Attenuation Coefficient: 0.2424 cm^{-1}

Highly effective for thermal neutron shielding, making it another strong alternative.

c) Less Effective Sample:
C1-5 (Serpentine Concrete):
- Gamma Attenuation Coefficient: 0.1799 cm^{-1}
- Thermal Neutron Attenuation Coefficient: 0.2155 cm^{-1}

Least effective for both gamma and thermal neutron shielding, making it the least desirable choice among the tested samples.

For applications requiring the highest level of radiation protection, B3-5 (Barite Concrete) is recommended due to its superior performance in attenuating both gamma and thermal neutron radiation. Other samples like M2-2 (Magnetite Concrete), M3 (Magnetite Concrete), and B1-1 (Barite Concrete) also offer good alternatives, with particular strengths in specific areas of radiation

attenuation.

This detailed analysis ensures that appropriate materials are chosen based on specific radiation protection needs, enhancing safety and effectiveness in various applications. This analysis aims to compare the linear attenuation coefficients (μ) for barite, serpentine, and magnetite concrete samples obtained in this study with results from other studies to validate the effectiveness of these materials in radiation shielding.

Other studies show that barite concrete has high linear attenuation coefficients for gamma rays, typically ranging from 0.180 to 0.190 cm^{-1} at different energies. This aligns well with our results, indicating that barite concrete is effective for gamma radiation shielding. Serpentine concrete generally has lower attenuation coefficients compared to barite and magnetite concretes. Studies have reported values around 0.175 to 0.185 cm^{-1} for gamma rays, which is consistent with our finding of 0.1799 cm^{-1}. This confirms that while serpentine concrete offers protection, it is less effective than barite and magnetite concretes. Magnetite concrete is known for its high density and effective shielding properties. Studies show linear attenuation coefficients for gamma rays ranging from 0.180 to 0.200 cm^{-1}, corroborating our results of 0.1815 to 0.1826 cm^{-1}. This suggests that magnetite concrete is highly effective for both gamma and thermal neutron shielding. This analysis demonstrates that the B2-4 and B3-5 samples have the best performance in reducing gamma radiation and thermal neutron intensity. These results can guide the selection of materials for constructing radiation shielding concrete. Samples with higher linear attenuation coefficients and lower HVL and TVL values exhibit better efficiency in radiation shielding.

3.4. Significance and Achievement:

The results of this study underscore the importance of selecting appropriate aggregates to optimize the mechanical strength, workability, and radiation protection properties of concrete. Magnetite and barite are particularly suitable for applications that require high strength and robust radiation shielding, while serpentine may be preferred in situations where better workability and moderate protection are required.

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